



# Prediction and validation of cloudless shortwave solar spectra incident on horizontal, tilted, or tracking surfaces

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## Abstract

The SMARTS spectral model can advantageously be used to predict clear-sky irradiance spectra on surfaces of any tilt and orientation, e.g., for the simulation of spectrally selective technologies like photovoltaic devices or coated fenestration systems. To evaluate the intrinsic accuracy of the model, its current version undergoes here a three-step validation exercise, involving reference radiative transfer codes, and two series of sophisticated spectral and ancillary measurements performed at different locations. Provided that the most important inputs are known with sufficient accuracy, it is concluded that the model performance is very high, with typical differences of 1–2% when compared to reference models, and uncertainties largely within the overall experimental error ( $\approx 5\%$ ) when compared to spectroradiometric measurements. The effect of imprecise spectral reflectance data of the foreground on the diffuse irradiance incident on shaded vertical surfaces is discussed.

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## 1. Introduction

Many biological, chemical and physical processes are activated more powerfully at some wavelengths than at others. This is especially true and important in the field of solar energy engineering, where spectrally selective systems such as photovoltaic (PV) devices, coated glazings, and biological reactors play an increasing role. For such systems, spectral radiation data are more appropriate than the usual broadband irradiance data. Unfortunately, spectral irradiance is usually not measured routinely, but only sporadically at a few experimental sites in the world. Consequently, the only way to accurately simulate the instantaneous energy production or overall performance of a spectrally selective system is to rely on appropriate model-

ing. (For system *rating* considerations, it is possible to use some pre-determined reference spectra, usually imposed by an ad hoc standard, but this method cannot be used to simulate a system under variable conditions, which is the purpose of this contribution.)

Most spectral radiation models have been developed for atmospheric research and have followed the footsteps of the well-known LOWTRAN code. Indeed, three of such rigorous radiative transfer models, LibRadtran (Mayer and Kylling, 2005), MODTRAN (Berk et al., 1999) and SBDART (Ricchiazzi et al., 1998), are used for reference in what follows. Even though they are highly considered in the atmospheric physics community because of their accuracy and physical capabilities, it appears that their complexity (conducive to slow execution), specialized inputs, and their lack of support for the prediction of spectral irradiance on tilted surfaces make their utilization inappropriate for energy applications.

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Engineering models such as SPCTRAL2 (Bird, 1984) are much simpler and more adapted to the problem at hand. However, their spectral resolution is limited, they have not been updated since the early 1980s, and their accuracy has not been tested against modern atmospheric models or measurements.

In the last few years, the more recent and sophisticated SMARTS model (Gueymard, 1995, 2001) has gained acceptance in both the atmospheric and engineering fields, due to its versatility (Gueymard, 2005), ease of use, execution speed, and various refinements.

MODTRAN, SBDART and SMARTS are three of six models that have been recently chosen to conduct an innovative radiative closure experiment (Michalsky et al., 2006). This study demonstrated that: (i) when detailed and accurate input data are available, such models can predict the clear-sky direct and diffuse *broadband* irradiances with

great accuracy; and (ii) SMARTS's broadband irradiance predictions are comparable to those of reference radiative transfer codes. These results also suggest that the current breed of such codes can be used for quality control purposes, to test the consistency of long time series of broadband irradiance measurements made with different instruments, for instance. However, the present study is aimed at determining to what extent these same models can be useful in predicting *spectral* irradiance on surfaces of various geometries.

Because spectrally selective technologies such as PV and thin-film coatings are very sophisticated and require considerable investments to develop and put into application, it is of paramount importance that the models used to predict the performance of these systems be of dependable accuracy under a variety of atmospheric conditions. The validation methodology followed here is threefold and consists in com-

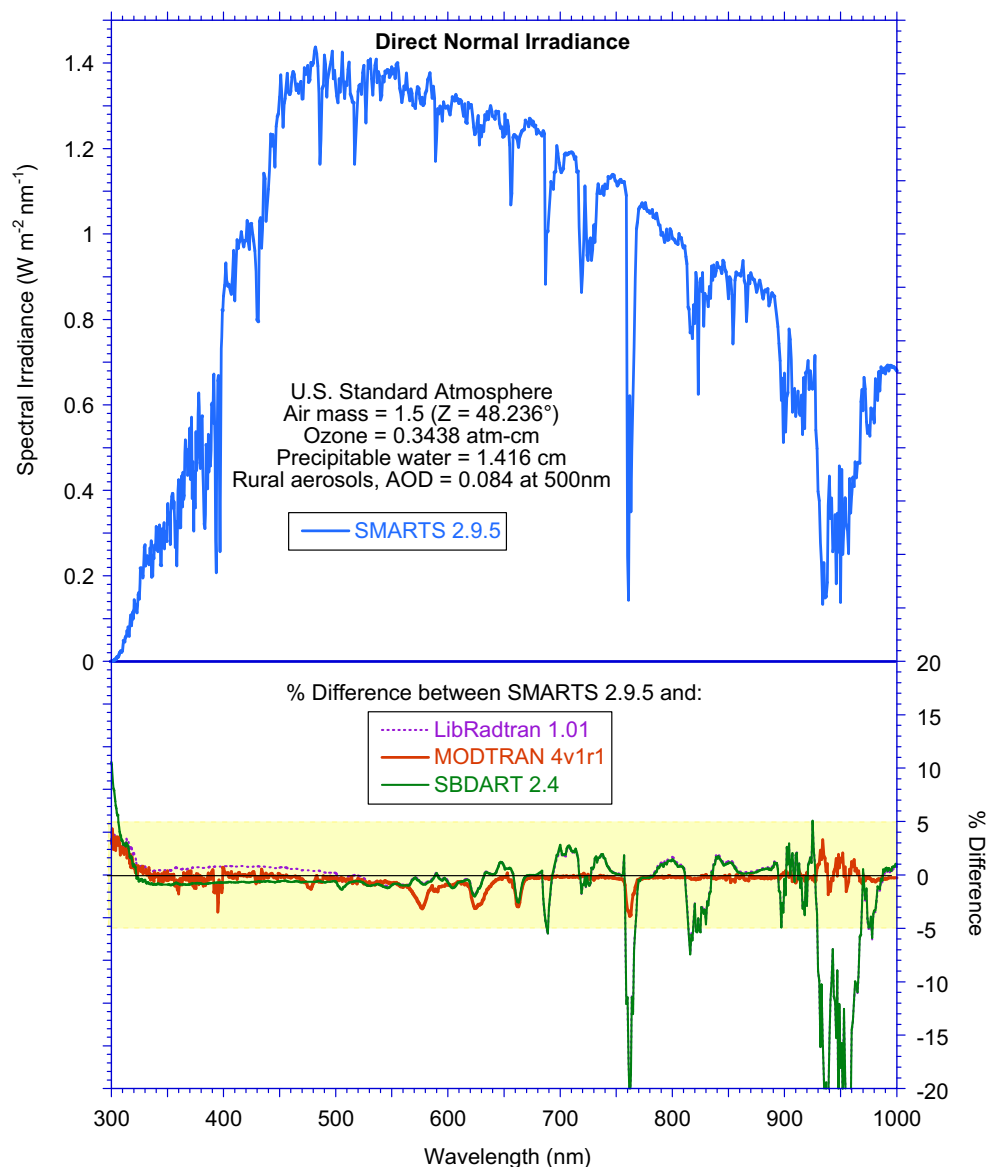


Fig. 1. Direct normal irradiance predicted by SMARTS for Case 1 (top panel), and spectrally smoothed percent difference between it and that predicted by three reference models (bottom panel) under the same ideal atmospheric conditions. The color-shaded area corresponds to an uncertainty of  $\pm 5\%$ .

paring the spectral predictions of SMARTS to: (i) those of three reference atmospheric models, under common and ideal atmospheric conditions for direct normal irradiance and global or diffuse horizontal irradiance (Section 2); (ii) experimental spectroradiometric measurements of direct normal irradiance and global or diffuse *horizontal* irradiance (Section 3.1); and (iii) experimental spectroradiometric measurements of global *tilted* irradiance that have been conducted specifically for this project (Section 3.2).

## 2. Theoretical validation

The first step into validating a model is to compare its predictions to those from more advanced or “reference” models. This is accomplished here by comparing SMARTS to the three advanced radiative transfer codes mentioned above: LibRadtran (Mayer and Kylling, 2005), MOD-

TRAN (Berk et al., 1999), and SBDART (Ricchiazzi et al., 1998). Such models are frequently used in fundamental atmospheric applications. Most of them have participated in detailed model intercomparison exercises (e.g., Halthore et al., 2005), which guarantee their robustness and accuracy. All models are here forced to use the same recent extraterrestrial spectrum (ETS) (Gueymard, 2004) to minimize sources of disagreement. Identical atmospheric conditions are also selected from the default vertical profiles they have in common. This guarantees that any model-to-model difference in irradiance prediction can be attributed entirely to differences in modeling the various extinction processes of the atmosphere.

Various ideal atmospheric conditions have been considered, so as to create a real validation framework, but only two typical cases are discussed here for conciseness. These two cases both consider a US Standard Atmosphere with

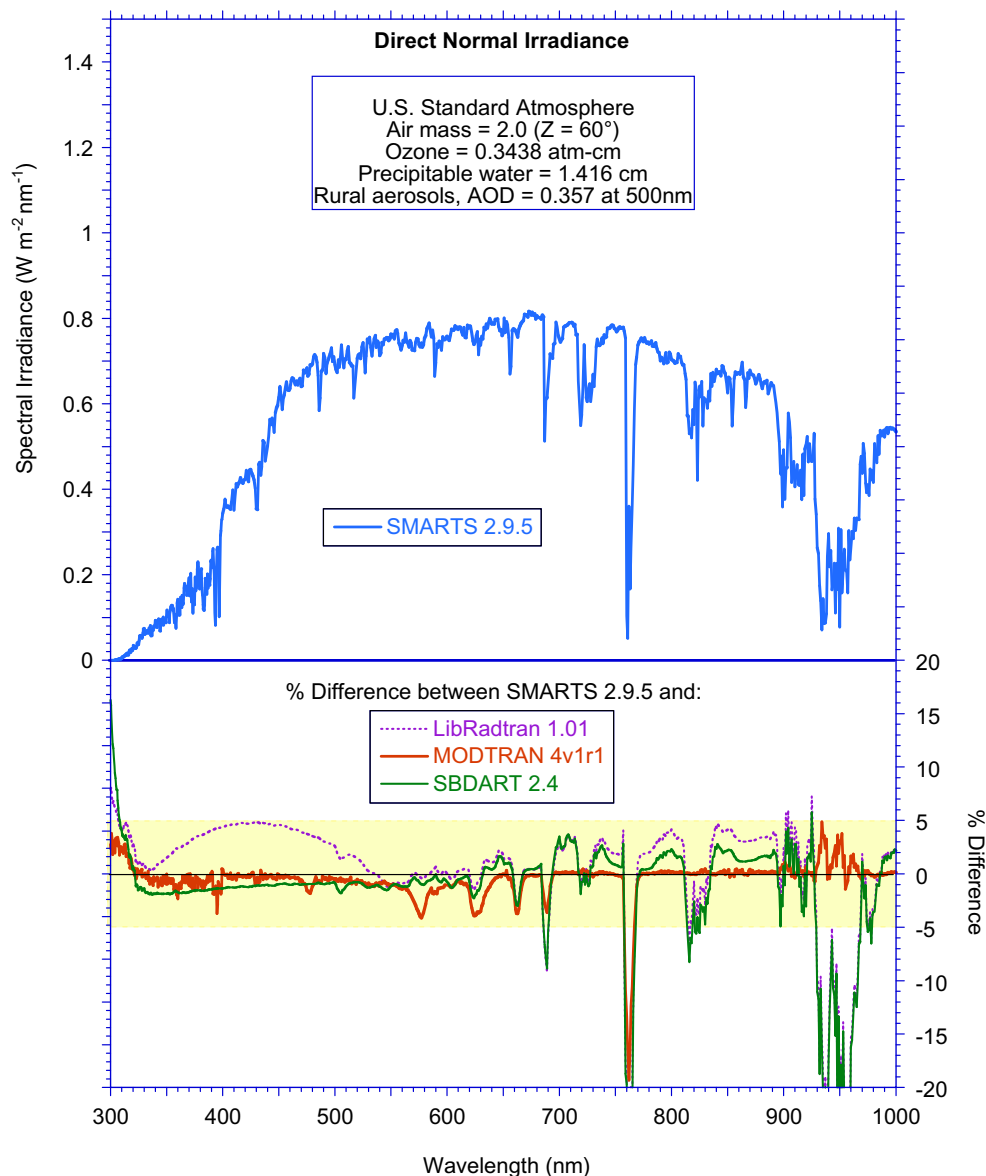


Fig. 2. Same as Fig. 1, but for Case 2: larger zenith angle ( $60^\circ$ ) and hazy conditions (AOD = 0.357 at 500 nm).

its corresponding columnar amounts of ozone (0.3438 atm cm) and water vapor (equivalent to 1.416 cm of precipitable water at sea level), standard pressure (1013.25 hPa), and an ideal ground with a spectrally constant reflectance of 0.2. *Case 1* is for a zenith angle of  $48.24^\circ$  (air mass 1.5) and relatively low turbidity, i.e., an aerosol optical depth (AOD) of 0.084 at 500 nm for a rural aerosol model (Shettle and Fenn, 1979). This whole set of variables reproduce the ASTM G173 standard conditions (ASTM, 2003) nearly exactly. (The only exception being ground albedo, considered spectrally flat here rather than variable in G173.) *Case 2* differs from *Case 1* in two respects only: zenith angle increases to  $60^\circ$  (air mass 2) and turbidity increases 4.25 times, to a spectral AOD of 0.357 at 500 nm.

Figs. 1 and 2 illustrate the results of this model inter-comparison that pertain to direct normal irradiance.

MODTRAN's spectral predictions are downgraded with a rectangular filter to match the resolution of both the ETS and SMARTS. The upper panel of the plots shows the spectral irradiance as predicted by SMARTS, whereas the bottom panel shows its percent difference compared to the three reference radiative transfer models. To increase legibility and avoid transient differences due to resolution artifacts, these differences have been smoothed with a 4-nm wide rectangular filter. Note the small differences (typically within  $\pm 1$ –2%) over most of the spectrum outside of strong absorption bands by oxygen (around 760 nm) and water vapor (around 940 nm). The LibRadtran and SBDART models use the same absorption data, explaining why their differences with SMARTS are the same in these bands. Compared to the two other reference models, MODTRAN uses more recent spectroscopic absorption data, and a different way of averaging them over short

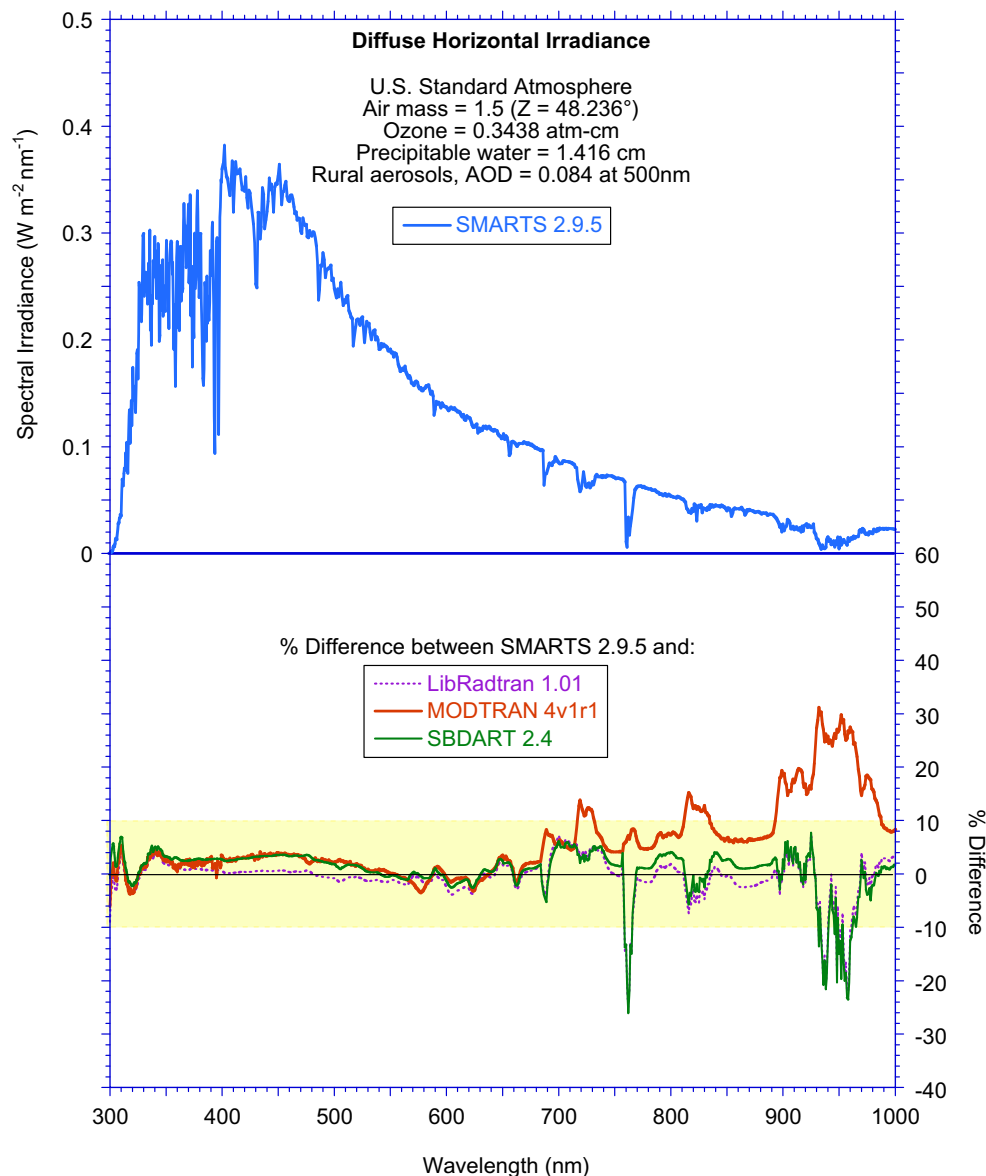


Fig. 3. Same as Fig. 1, but for diffuse irradiance.

spectral intervals with so-called “broadband models”, yielding different results in these bands. Although relative model-to-model differences may be high within these absorption bands, they are associated with very low irradiances, and are therefore insignificant in most applications.

Similar results, but for diffuse irradiance, appear in Figs. 3 and 4, showing slightly larger relative differences (typically within about 5% in the visible) than in Figs. 1 and 2. This could be expected because diffuse irradiance is more difficult to model and involves more variables than direct irradiance. In both figures, the spectra predicted by SMARTS are closer to those of LibRadtran than to those of MODTRAN or SBDART. As with direct irradiance, the strong absorption bands induce larger differences, whose sign varies depending on which reference model is selected. More insight about this is gained from Fig. 5, where the absolute difference between the spectra obtained by SMARTS and MOD-

TRAN are shown for the two cases. This difference is normally less than  $0.01 \text{ W m}^{-2} \text{ nm}^{-1}$  for direct irradiance and  $0.02 \text{ W m}^{-2} \text{ nm}^{-1}$  for diffuse irradiance. For direct irradiance, notable exceptions appear as downward-looking spikes, and correspond either to the strong oxygen absorption band (around 760 nm), or to secondary absorbers (particularly the oxygen collision complex,  $\text{O}_2\text{-O}_2$ ) that are considered in SMARTS but not in MODTRAN. Results for global irradiance are shown elsewhere (Gueymard, 2007). They are similar to those for direct irradiance since, under clear skies, global irradiance is mostly made of its direct component.

Figs. 1–5 provide qualitative information about the performance of SMARTS. Detailed statistics describing the quantitative performance of SMARTS relatively to reference models would be worthwhile. However, each application requires a specific spectral range, and different models

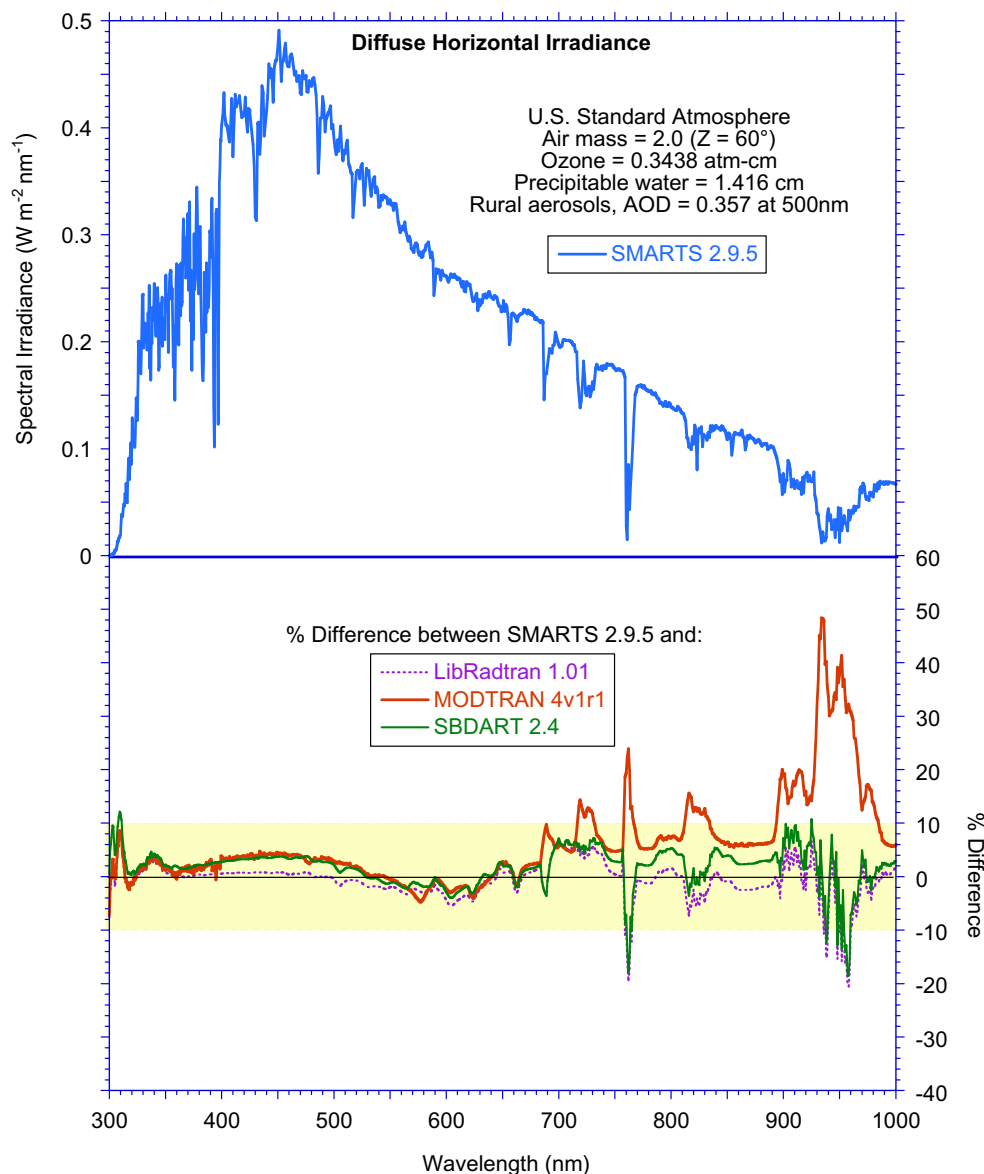


Fig. 4. Same as Fig. 2, but for diffuse irradiance.

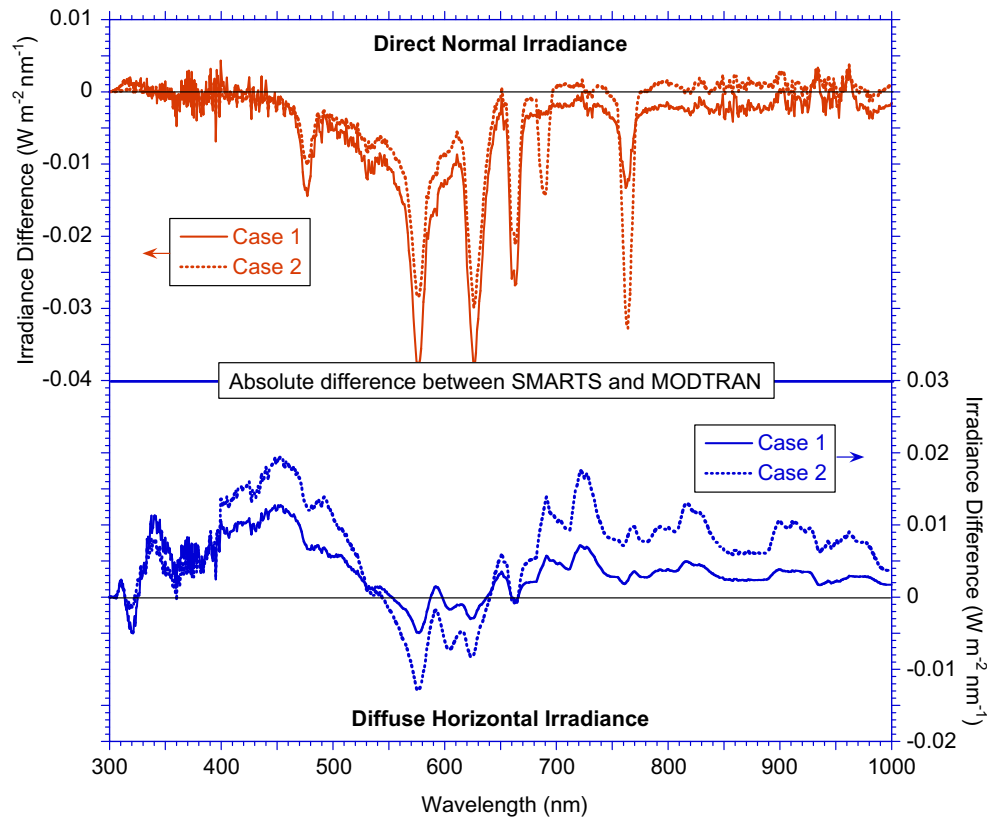


Fig. 5. Absolute difference (in  $\text{W m}^{-2} \text{nm}^{-1}$ ) between the spectral direct (top panel) and diffuse (bottom panel) irradiances predicted by SMARTS and MODTRAN for the two cases described in the text.

Table 1

Broadband irradiances predicted by SMARTS, and percent differences between them and those from three reference models or their average, for the two cases described in the text

	Irradiance ( $\text{W m}^{-2}$ )					
	Case 1			Case 2		
	Direct	Diffuse	Global	Direct	Diffuse	Global
	854.2	99.1	668.0	555.5	162.9	440.6
LibRadtran 1.01	0.2	0.5	0.3	1.7	0.2	1.1
MODTRAN 4v1r1	−0.6	3.2	0.0	−0.5	3.6	0.9
SBDART 2.4	0.1	1.8	0.4	0.8	1.9	1.2
Average (%)	−0.1	1.8	0.2	0.6	1.9	1.1

can be arbitrarily selected to become the ultimate reference, which seriously complicates the issue. Nevertheless, a limited evaluation of the average performance of SMARTS can be obtained when considering the whole 290–4000 nm spectral range. Total broadband irradiances are obtained for each model with the trapezoidal rule. The percent differences between the predictions of SMARTS and those from the other models are compared in Table 1. These numbers also represent the overall mean bias differences between the SMARTS *spectral* predictions and those from each reference model. It is found that SMARTS's performance for direct irradiance is better than 1% for the two cases, and better than 2% for diffuse irradiance,

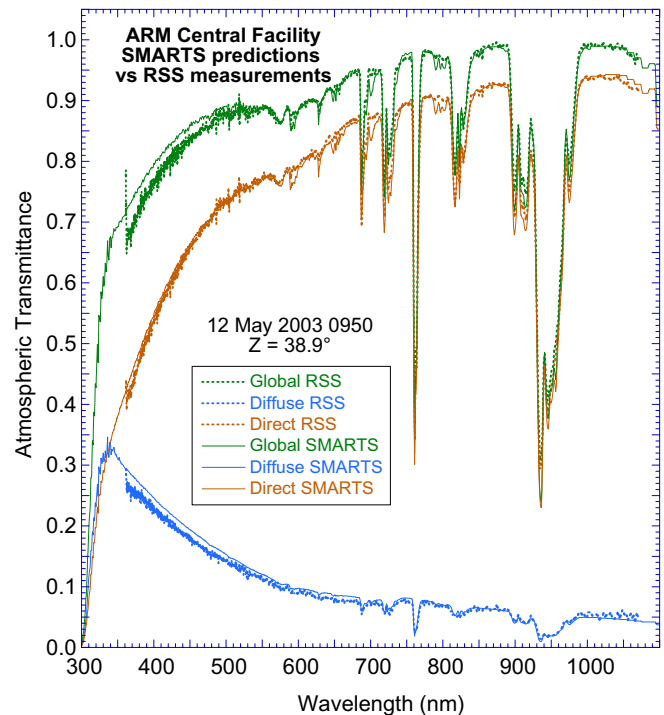


Fig. 6. Predicted vs measured direct normal, global and diffuse transmittances at ARM-SGP for a clear day.

when compared to the mean irradiances from the three reference models. The relative results presented here cannot



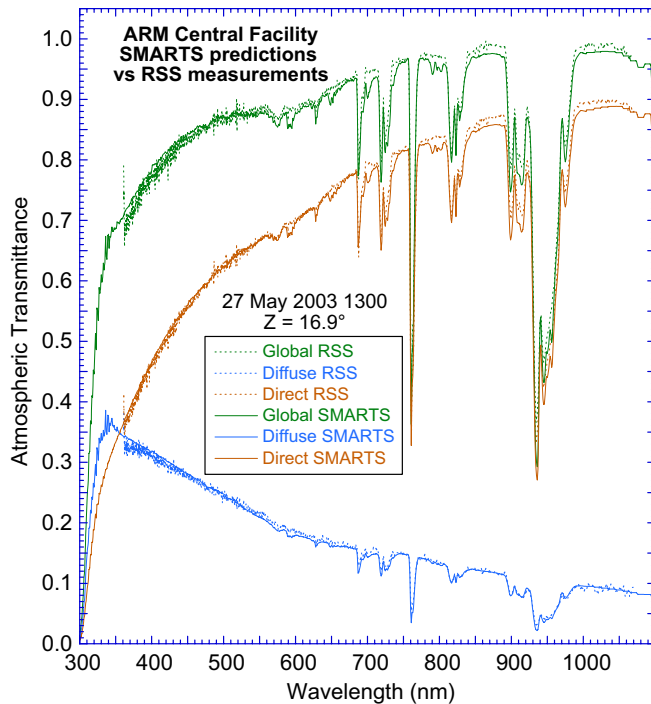


Fig. 7. Same as Fig. 5, but for a hazy day and higher sun.

provide the absolute accuracy of SMARTS at each individual wavelength, but can at least confirm its overall consistency relative to more advanced models.

There is no known atmospheric model that can predict spectral irradiance on tilted planes. When such prediction is indeed necessary in atmospheric physics (e.g., for remote sensing over steep terrain), the only alternative consists of using an appropriate Monte Carlo model, which resolves the problem statistically rather than deterministically. Monte Carlo models are extremely complex, however,

and involve very long calculation times. Furthermore, their absolute accuracy in predicting irradiance incident on tilted surfaces of small sizes, and the repeatability of such a process, are not known precisely. Usage of this type of model is therefore not a viable option in the present context, so that only an experimental validation is considered in what follows.

### 3. Experimental validation

#### 3.1. Conventional measurements

Conventional measurements and validation refer here to direct normal irradiance and diffuse or global irradiance on a horizontal surface. This corresponds to the irradiance that would be incident on tracking and horizontal flat receivers, respectively. Most spectral measurements currently performed are of this type.

Comparisons between SMARTS's predictions and measured spectra have always been an important part of the model's development process to guarantee its relevance and accuracy (e.g., Gueymard, 1995, 2001, 2005; Gueymard et al., 2002). The results provided in this series of publications suggested that the model could perform well relatively to experimental data. Therefore only a few recent and more advanced sources of data are discussed here.

The main difficulty in any experimental validation undertaking of this type is that very stringent requirements must be met if one wants to evaluate the accuracy of the model alone. Ideally: (i) the spectrometer should have a better absolute accuracy than the model under scrutiny (otherwise the model actually tests the performance of the instrument); (ii) all the inputs required by the model should be measured simultaneously with independent



Fig. 8. Left: Deployment of an ASD field spectrometer at NREL in 2005. Right: Ground cover seen by the instrument from its inverted position. (Photos courtesy Daryl Myers.)

instrumentation; and (iii) these inputs should be “perfectly” accurate to avoid propagation of errors.

Conditions for this ideal closure experiment unfortunately never happens, due to various limitations. For most validation exercises, only a few important input variables can be measured independently, and their accuracy is neither perfect nor well known. In recent years, the Southern Great Plains (SGP) facility of the Atmospheric Radiation Measurement (ARM) program (located near Lamont, OK) has maintained a wealth of collocated radiometric and meteorological instruments. The high-quality and redundant measurements obtained during the Aerosol Intensive Observation Period (AIOP) of May 2003 currently offer one of the best opportunities to compare model predictions to irradiance measurements (Michalsky et al.,

2006). The AIOP’s ancillary measurements include AOD from various sensors, aerosol single-scattering albedo, aerosol asymmetry parameter, and precipitable water (PW).

SMARTS predictions are here compared to rotating shadowband spectroradiometer (RSS) measurements at the SGP site. This instrument uses a 1024-pixel CCD, measures global and diffuse horizontal irradiances alternatively (quasi-simultaneously), and calculates direct irradiance by difference between them, in the spectral range 360–1070 nm (Harrison et al., 1999). A sophisticated calibration technique, based on frequent Langley plots and detailed statistical analysis (Kiedron, 2006), has recently produced a method to obtain highly accurate *transmittances* from the irradiance dataset available from <http://iop.archive.arm.gov>, thus avoiding uncertainties in the instrument’s



Fig. 9. Partial scene viewed by a vertically mounted sensor when facing south. (Photo courtesy Daryl Myers.)

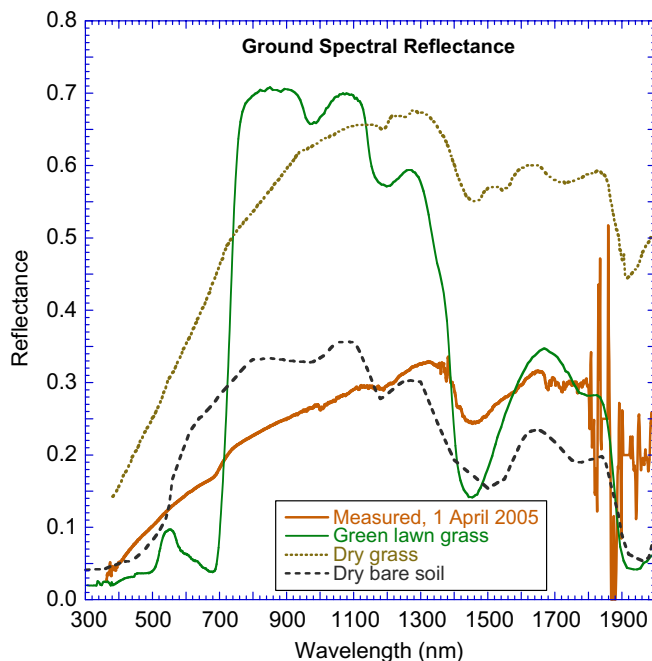


Fig. 10. Comparison between the foreground’s spectral reflectance measured at NREL on April 1, 2005 and that from typical ground covers.

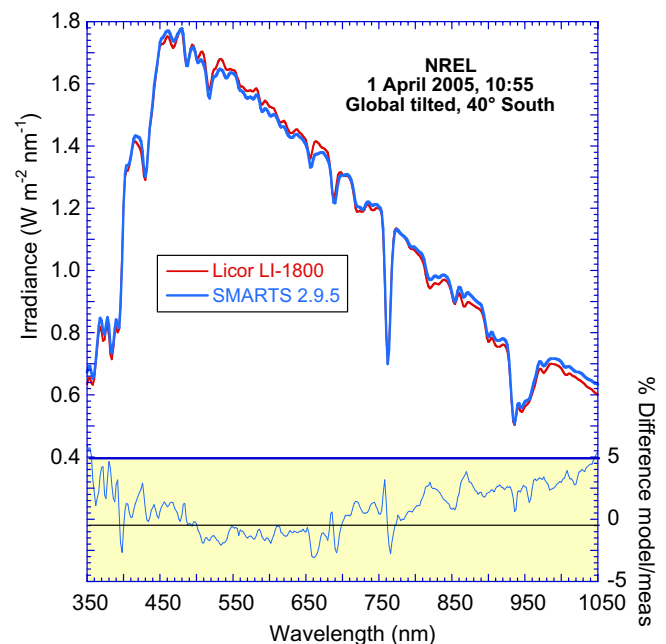


Fig. 11. Modeled vs measured spectrum on a 40°-tilted plane facing south under very clear conditions.



absolute calibration and in the ETS. To better simulate the RSS, the SMARTS predictions are smoothed with a Gaussian filter of variable bandwidth, increasing (0.38–3.8 nm) non-linearly as a function of wavelength (Kiedron, 2006). For all these comparisons, the most important atmospheric variables were determined from collocated instruments, as summarized elsewhere (Michalsky et al., 2006).

Typical results appear in Figs. 6 and 7 for two of the 30 cases that were considered in the aforementioned study (Michalsky et al., 2006), covering conditions with low AOD (12 May 2003) and with high AOD (27 May 2003), respectively. Both figures show good to excellent agreement over most of the spectrum, and are representative of all the similar results gathered during the AIOP. Nevertheless, a “perfect” match can happen only if the main aerosol optical properties are known with sufficient accuracy. This may not be perfectly the case in Fig. 6, explaining the slight and progressive biases below 700 nm, where aerosol scattering is most intense.

### 3.2. Measurements on tilted planes

Fig. 8 shows a part of the experimental setup that was purposefully deployed at the Solar Radiation Research Laboratory (SRRL) of the National Renewable Energy Laboratory (NREL) in Golden, CO during April 2005 to undertake this final part of the study. A portable ASD FieldSpec spectrometer, equipped with three solid-state detectors and capable of acquiring spectra between 350 and 2500 nm at high speed ( $\approx 100$  ms per spectrum), was deployed. The instrument’s bandwidth varies between 3 and 10 nm, depending on detectors, whose crossover wavelengths are 995 and 1800 nm. A more conventional, laboratory-grade Optronic OL-754 scanning spectroradiometer was also deployed to acquire spectra between 300 and 800 nm in 3 min. This instrument’s nominal bandwidth is 5 nm. In addition, data from a fixed Licor LI-1800 field instrument, which is permanently installed on a  $40^\circ$ -tilted plane facing south, have also been used. This instrument has a 6.5-nm bandwidth, and routinely takes spectral scans every five minutes. All these radiometers are regularly calibrated in the laboratory against NIST-traceable standard lamps. Langley plots conducted on April 1, a very clear day, allowed a fresh calibration of the co-located sunphotometers using the usual Langley method. The AOD at four wavelengths was retrieved at 1-min intervals. For each set of AOD results, the Ångström wavelength exponent,  $\alpha$ , was also obtained as usual, by fitting the spectral variation of AOD with wavelength to Ångström’s law.

Contrarily to the two ARM cases described in Section 3.1, no measurement of the other aerosol optical properties (single-scattering albedo and asymmetry parameter) is made at SRRL, so that default values were used in SMARTS. These variables are of second-order importance compared to AOD or  $\alpha$ , and only affect diffuse irradiance. Additionally, the local PW measurements normally made

with the dedicated 942-nm channel of a sunphotometer could not be used because of recurrent problems. However, it was possible to derive PW from 1-min temperature and humidity data using a validated empirical method (Gueymard, 1994). These PW estimates compared satisfactorily to radiosonde data obtained twice daily at Denver’s airport (27 km away), and to data obtained at Boulder (about 30 km away) with both a sunphotometer of the AERONET network (every 15 min) and a GPS receiver (every 30 min). The uncertainty in PW thus obtained is estimated at about 15%, which is of insignificant consequence for spectral irradiance predictions outside of strong water vapor bands.

An estimate of the ground’s spectral reflectance was obtained by rationing the upwelling and downwelling global fluxes measured by the FieldSpec instrument on one mid-day occasion (Fig. 8). This simple measurement, however, is not necessarily representative of the real foreground reflectance facing a tilted instrument. For instance, the partial scene viewed by a tilted sensor facing south appears in Fig. 9. Note that the ground cover is globally different from what appears in Fig. 8, and that there is significant sky shading above the horizon, where radiance is quite high under clear skies. Furthermore, the measurement was made on April 1, 2005 when the grass was dry. The upward and downward fluxes were measured from a height of only about 1 m from the ground, and might have captured a significantly larger fraction of bare ground than what would actually be “detected” by a vertical plane. This is indirectly illustrated in Fig. 10, where the actual measured reflectance is compared to typical values for green lawn grass, dry grass, and dry bare soil. The data for the latter three surfaces are from the albedo library in SMARTS. Note the obvious difference in spectral reflectance shapes between

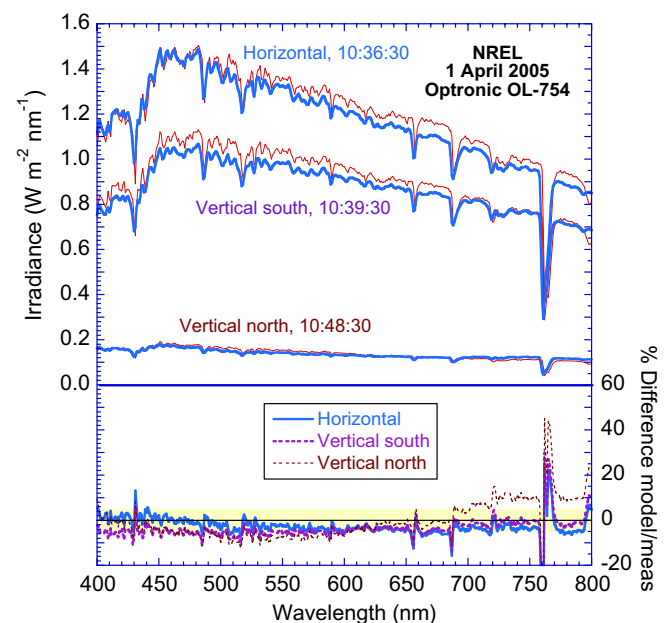


Fig. 12. Predicted vs measured global spectra at NREL (top) under very clear conditions, and percent difference between them (bottom).

green grass and soil, and the strong increase in green-grass reflectance around 700 nm, which corresponds to the upper limit of the photosynthetic absorption band ( $\approx 400$ –700 nm) and is therefore characteristic of live vegetation in general. It is clear from Fig. 10 that the spectral shape of the measured albedo is closer to that of dry soil than of dry grass, and is far from that of green grass. Furthermore, some surfaces reflect more anisotropically than others. All this greatly increases the uncertainties when comparing measured and predicted spectra, relatively to the simpler cases of Section 3.1. These adverse circumstances must be borne in mind when interpreting the results that follow.

A typical comparison between SMARTS and a measured global spectrum on a  $40^\circ$ -tilt south-facing plane appears in Fig. 11. The difference between the two spectra is within  $\pm 5\%$ , which is excellent, and its wavy structure can be explained in great part by known instrumental lim-

itations (Carlund et al., 2003; Gueymard et al., 2002). The spectral measurement was made on the same day as the albedo measurement just described above. The contribution from the ground-reflected flux is very limited in this case anyway, owing to the fact that diffuse irradiance is only a small part of the total irradiance, and to the small tilt. The latter's ground view factor,  $(1 - \cos(\text{tilt}))/2$ , is only 0.117, compared to 0.5 for a vertical plane.

For the same day again, three spectra measured with the OL-754 instrument in a 12-min interval timeframe are compared to the model's predictions in Fig. 12. Interestingly, AOD was particularly low (0.027 at 500 nm) that day. Combined with reduced Rayleigh scattering due to the site's high altitude (1829 m), little diffuse radiation is produced, hence the very low irradiance on the north-facing vertical plane. Despite all the modeling and experimental difficulties of this exercise, predictions are still mostly within  $\pm 5\%$  of measurements.

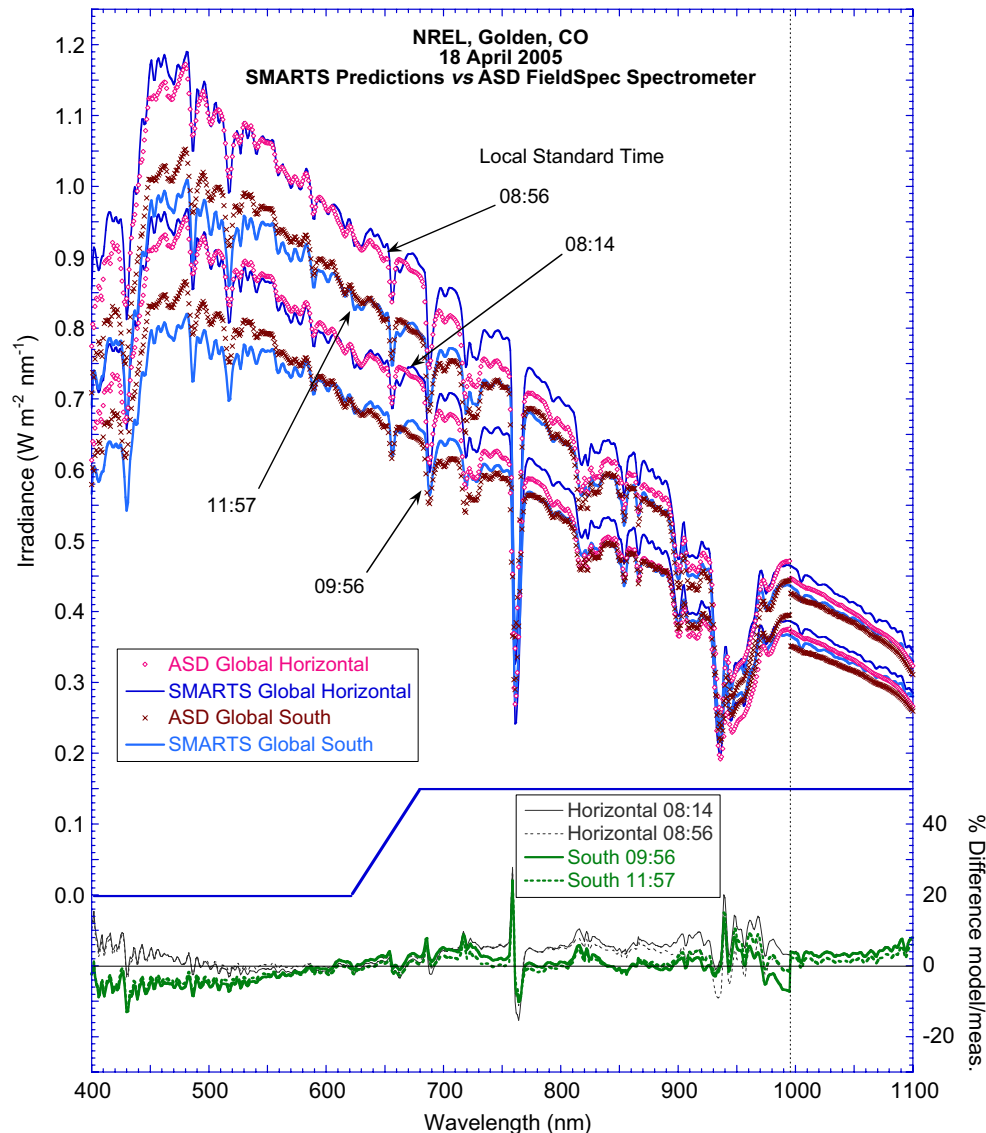


Fig. 13. Predicted vs measured global spectra at NREL (top) on directly sunlit surfaces, and percent difference between them (bottom).

Typical SMARTS predictions of global irradiance for surfaces in the sun and in the shade are compared in Figs. 13 and 14, respectively. In these two figures, the reference experimental spectra were all acquired with the FieldSpec instrument during the morning of April 18, i.e., 17 days after the albedo measurement shown in Fig. 10. Two global–horizontal spectra appear in Fig. 13, along with two global spectra incident on a south-facing vertical surface. Fig. 14 rather presents spectra for a north-facing and a west-facing vertical planes. As could be expected, the irradiance on surfaces in the shade is considerably less than that on sunlit surfaces (note the change in scale of the Y-axis between the two figures).

Good agreement between model predictions and measurements is found for the sunlit surfaces, overall (Fig. 13). Larger relative differences are found in the case of the vertical surfaces in the shade, however (Fig. 14). The irradiance on the north-facing surface is not directly comparable to that in Fig. 12 for various reasons: (i) the

sun's zenith angle is  $57.4^\circ$  and  $38.9^\circ$  (corresponding to air masses of 1.9 and 1.3) in Figs. 14 and 12, respectively; (ii) similarly, the sun's incidence angle on the north vertical surface in the two cases is  $101.5^\circ$  and  $122.6^\circ$ , respectively; (iii) AOD at 500 nm is 0.108 in the case of Fig. 14, i.e., four times more than that of the previous case, conducive to increased diffuse irradiance; and (iv) ground cover has changed due to seasonal effects (Spring time). Taking into account that the view factors for the sky and ground are equal (to 0.5) in the case of a vertical surface, it is obvious that the irradiance incident on such a surface is significantly affected by ground reflections when shaded from the direct sun. Unfortunately, no albedo measurements were made that day, so that the spectral reflectance data of April 1 had to be used.

The percent irradiance differences displayed in the bottom panels of Figs. 14 and 12 show a strong change of pattern around 700 nm that only affects the north and west orientations on April 18. This cannot be explained by

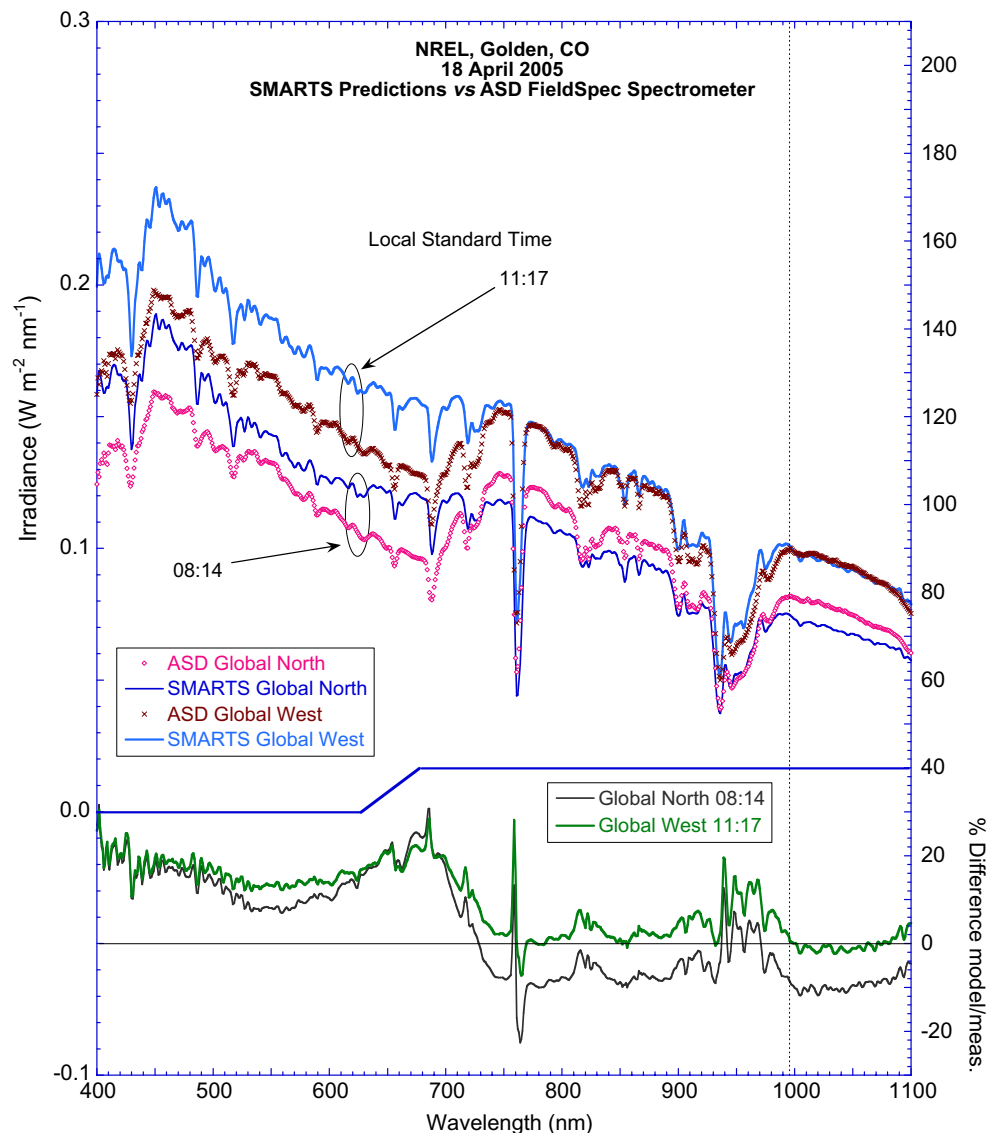


Fig. 14. Predicted *vs* measured global spectra at NREL (top) on shaded surfaces, and percent difference between them (bottom).

atmospheric effects because a similar pattern would also appear in Fig. 13. It is therefore argued that the discrepancy is mostly caused by changes in ground reflectance, induced by denser and greener grass on April 18 than on April 1. This effect is compounded for other orientations, because large reflecting obstructions exist at this site, as described elsewhere (Gueymard, 2007), yielding inconsistent results.

For experimental validation purposes, the present findings strongly suggest that detailed spectral albedo measurements need to be acquired around the place and time of the main experiment, whose location must be carefully chosen to be free from any obstruction or parasitic reflection. From a different standpoint, which would be that of most applications in practice, it can be very difficult to accurately predict spectral irradiances on shaded vertical surfaces if the spectral reflectance of the immediate ground is not precisely known, which is generally the case. Investigations are underway to quantify the related uncertainties, using both modeled and experimental data.

#### 4. Conclusion

This study confirms the excellent accuracy of the SMARTS spectral model by comparison to predictions from reference models and to high-end experimental data at the SGP site. Validating modeled spectra for tilted, tracking or vertical planes is more challenging because additional variables are introduced, and some are difficult to model or control in practice (e.g., horizon shading or reflectance characteristics). Despite these difficulties, the special measurements carried out at NREL have shown that it is indeed possible to obtain accurate irradiance spectra on tilted or vertical planes with SMARTS. This is fortunate because it liberates the end-user from the extreme complexity of Monte Carlo models, which are required in remote sensing applications over steep terrain, for instance.

These results are all the more important and original that no similar undertaking with such a large scope has been found in the literature. For any receiver geometry and under any cloudless atmospheric condition, SMARTS therefore appears ideal to help simulate the output of spectrally selective devices. The accuracy of this model is normally within 1% for direct irradiance or 2% for diffuse irradiance when compared to more sophisticated atmospheric models, and within the instrumental uncertainty ( $\approx 5\%$ ) when compared to high-quality measured irradiance spectra. For realistic situations under cloudless skies, the most important variable that conditions the accuracy of the predicted spectra is AOD. For optimum results, this variable needs to be measured in real time with a collocated sunphotometer. For steep receivers, such as vertical PV panels or fenestration systems, precise evaluation of the foreground's reflectance properties and of horizon shading

is essential too. Lack of such data may seriously hinder the model's performance, particularly when the surface is not directly sunlit.

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